PIP-II Phase-II Beam Commissioning Plan

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Document Approval

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1. Purpose

The objective of this document is to describe the beam commissioning plan for the PIP2IT Phase-II commissioning.

2. Acronyms

HEBT	Heigh Energy Beam Transport
HWR	Half Wave Resonator
MEBT	Medium Energy Beam Transport
PIP-II	Proton Improvement Plan II Project
PIP2IT	PIP-II Injector Test
RF	Radio Frequency
SSR1	Single Spoke Resonator Type 1

3. Introduction

PIP2IT serves as testbed for PIP-II technologies. PIP2IT consist of the Warm Front End followed by two SRF cryomodules: Half-Wave Resonator (HWR and Prototype Single-Spoke Resonator Type 1, which we will refer to simply as SSR1, and the High Energy Beam Transport (HEBT) line that brings the beam to a high-power dump (Figure 3-1) inside a radiation shielding housing. The Warm Front End, the connection between the two cryomodules, which houses a vacuum pumping station, and the HEBT are at room temperature. The SRF cryomodules are nominally operated at 2K.

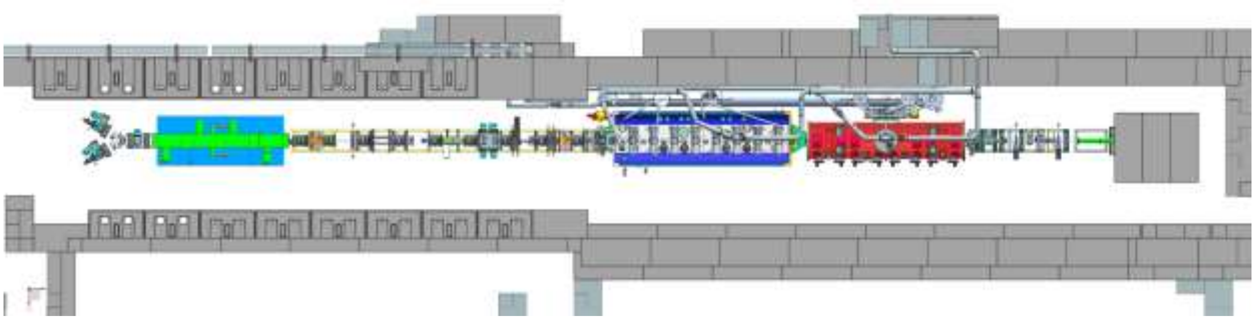

Figure 3-1 PIP2IT layout (top view)

The beam is generated by the ion source assembly at 30 kV. A LEBT chopper forms macro-pulses. The beam is then accelerated to 2.1 MeV by the RFQ and propagates through the MEBT, where longitudinal focusing is accomplished with three copper bunching cavities operating at room temperature. A fast, bunch-by-bunch chopper, consisting of two fast kickers and a beam absorber, is situated in MEBT. The chopper produces a preprogrammed bunch pattern to enable direct injection of linac bunches into

Booster RF buckets. After MEBT, the beam is accelerated to 10 MeV through the HWR and to up to 22 MeV in the SSR1 and transported to the beam dump at the end of HEBT. Transverse focusing is accomplished with either superconducting solenoids inside the cryomodules or quadrupole magnets in MEBT and HEBT. Steering dipoles provide orbit correction.

PIP2IT beamline is equipped with beam diagnostics required to tune the beam and measure its parameters: beam current monitors (for pulsed and DC beam), beam position monitors, beam transvers profile monitors, emittance scanners, beam longitudinal profile monitors and other miscellaneous beam pickups, collimator scrapers, and electrically isolated electrodes, some of which being integrated in the Machine Protection System (MPS).

The PIP2IT beam commissioning consist of two phases:

- Phase 1: Warm-front end
- Phase 2: HWR, SSR1, and HEBT

The warm front end was successfully commissioned in 2017-2018. A summary of the commissioning results for Phase I is given in Appendix A. Phase 2 commissioning is planned in 2020. The goals and the commissioning approach for Phase 2 are described below.

4. PIP2IT Phase-II Goals

Phase II of PIP2IT brings a great deal of new hardware such as cryomodules and SRF. Some of the newly installed hardware such cryomodules are on the critical technology roadmap. A demonstration of their functionality, even without beam, is important for the project success. This section describes high level goals and priorities for PIP2IT Phase II. Goals specific to beam commissioning are shown in Section 6.

The goals for PIP2IT are shown below:

- Demonstrate critical technologies for the PIP-II project and integrate lessons learned during equipment testing into the final design of production systems.
- Commission HWR and SSR1 cryomodules with beam. Demonstrate acceleration of the H- beam by SRF cryomodules. Verify optics and alignment of cryomodules components. Test accelerator systems with the beam and integrate lessons learned.
- Conduct additional tests and studies aimed at improving reliability, stability, and understanding of limits
- Gain experience with installation, integrated testing, and operation of PIP2IT equipment, including SRF/RF systems, and develop and validate corresponding processes and procedures

Phase 2 beam commissioning includes re-commissioning of the Warm Front End before connecting the vacuum pipe to the HWR (or, at least, before making the WFE’s vacuum common with the HWR’s). Beyond merely re-establishing beam after a long shutdown, the main goal of the WFE re-commissioning activities is to test instrumentation after implemented upgrades (e.g. BPMs) and develop the MPS to a state that brings confidence that the cryomodules are protected against beam-induced incidents.

5. Beam Parameter Envelope

The PIP2IT beam parameter envelop is defined to be consistent with the approved PIP2IT shielding assessment [1]. These parameters correspond to the nominal operations for LBNF.

Table 5-1 Beam parameters Envelope

Parameter	Nominal value	Unit
Energy	25	MeV
Pulse length	550	μs
Beam intensity per any given hour	4.95E17	H- per hour
Current averaged over 1 μs	2	mA

6. Beam Commissioning Goals

Completion of the beam commissioning goals signifies success of the PIP2IT beam commissioning and demonstrates ability of PIP2IT systems to accelerate the beam. Achieving commissioning goals is recommended before conducting other beam measurements listed in Section 13.

Primary beam commissioning goals:

- Accelerate beam to 22 MeV and verify its energy in HEBT

If time permits, complete additional beam commissioning goals:

- Evaluate beam properties in HEBT with parameters shown in Table 2. The beam transport might need to be tuned and beam optics measured before the beam parameters are measured.

Table 6-1 Expected beam parameters in HEBT

Beam parameter	Goal / Nominal value	Accuracy of the measurement
Beam energy	22 MeV	±2 %
Current (averaged over 1 μs)	2 mA	±1.5 %
Transmission through both cryomodules	99%	±2 %
Transverse emittance (rms, normalized, each plane)	0.25 μm	±10 %
Longitudinal emittance (rms, normalized)	0.4 μm	±20 %
Bunch extinction	$< 5\times10^{-3}$	$\pm10^{-3}$
Transverse phase space distributions	N/A	0.5% (relative)

It is expected that beam commissioning will provide important information on

- Alignment of cavities and solenoids
- Impact of beam losses on performance cavities and solenoids

- Validation and calibration of models of cavities and solenoids
- Emittance growth during acceleration
- Halo tail growth

Functionality of critical instrumentation (BPMs, ACCTs) and MPS will be verified as part of commissioning

7. Roles and Responsibilities

Personnel roles and responsibilities in respect to PIP2IT commissioning are defined in [2].

8. ES&H

PIP2IT is simple-geometry, single-room accelerator with no extractable beam, single entry point, and produces only local work area impacts. As such, PIP2IT fits within an exemption in the Accelerator Safety Order DOE O 420.2C and is managed under the provisions of Title 10, Code of Federal Regulations (CFR), Part 835 and Part 851, Fermilab Environment, Safety and Health Manual (FESHM), and the Fermilab Radiological Control Manual (FRCM). The facility is not included in the Fermilab SAD and ASE. It is listed in the laboratory Radiation Generating Device Inventory.

8.1. Hazard Analysis Document

Potential hazards associated with executing the PIP2IT program were identified, analyzed, and documented in the PIP2IT Hazard Analysis Document (HAD) [3]. The document identified hazards associated with non-beam and beam related activities. They relate to the ion source's hydrogen gas system, high voltage electrical equipment, high power RF, cryogenic equipment (including Oxygen Deficiency Hazard) and potential x-ray production by RF cavities and beam-related ionizing radiation hazards. Therein, descriptions of engineering controls and administrative measures used to eliminate, control or mitigate the hazards from accelerator operation are presented.

8.2. Shielding assessment and radiological protection

Radiological Shielding Assessment (SA) for 25 MeV operations has been developed [1]. The SA was reviewed by the Fermilab Shielding Assessment Review Panel, consisting of Fermilab scientists, engineers, engineering physicists and radiation safety staff. The Senior Radiation Safety Officer has approved SA. Table 5-1 shows approved beam parameters.

The exclusion area around the machine is set for personnel protection in accordance with the FRCM. The facility is equipped with radiation monitors, interlocked to the enclosure Radiation Safety Interlock System, that will drop the beam permit if the measured radiation level exceeds allowed limits. The location of the radiation monitors was determined based on results of the shielding assessment. In addition, residual activation of beam line components will be measured periodically and compared against predicted values and administrative limits to keep activation within limits.

8.3. Subsystem Operational Readiness Clearance (ORC)

To ensure operational safety of installed components, commissioning of subsystems follows Operational Readiness Clearance process described in FESHM, Chapter 2005. All systems are reviewed Subject Matter Experts (SEM, i.e. cryo, RF, etc.) and the ORC Committee before granting authorization to operate. PIP2IT system owners or their delegates are responsible for completing ORC. The PIP-II ES&H Manager is responsible for coordination of ORC.

List of ORCs for commissioning activities identified:

- LEBT – ORC to obtain clearance to restart beam testing of LEBT
- RFQ and MEBT – ORC to obtain operational clearance to operate RFQ and MEBT
- MEBT – 200 Ohm Kicker
- HWR – Cryo Panel review for cooldown
- HWR – RF Amplifiers powered to dummy loads, Completed
- HWR – Cold RF Testing
- SSR1 – Cryo Panel review for cooldown
- SSR1 – Cold RF Testing (Several ORCs can be required if amplifiers will be delivered by an In-Kind Contributor in several batches)
- HEBT – ORC to obtain clearance to operate HEBT
- Laser Instrumentation LSO Review and approval

8.4. Beam Operation Readiness

The PIP2IT facility falls within the single room accelerator exemption in the DOE Accelerator Safety Order 420.2C. As such, the facility will be operated as a Radiation Generating Device (RGD) in accordance with FESHM and the FRCM. However, a graded approach is being applied to incorporate a best practice from DOE O 420.2C by including an internal Operational ORC to obtain approval to accelerate beam through cryomodules to the HEBT dump. The Operational ORC will focus on operational readiness aspects of PIP2IT.

9. Conduct of operations

9.1. Personnel training and operator qualification

Beam operations can be conducted only by “qualified operators”. At least one qualified operator is required on shift. The training will be on-the-job (OJT), consisting of demonstrations how operate equipment and supervised tests demonstrating trainee’s understanding of operation procedures. The training instructions will be document, maintained, and version controlled. The Operations Coordinator or his/her delegate will train and qualify PIP2IT operators according to the Qualified Operator Procedure [4]. The Operations Coordinator will maintain the record of qualified operators.

OJT will be updated as new system will become operational. OJT updates for specific systems will be provided by systems owners and included in the training by the Operations Coordinator.

In addition to training specific to the operation of PIP2IT, personnel need to maintain the proper safety training commensurate with their work (e.g. LOTO, ODH, Radiological Worker, etc.).

9.2. Control Rooms and Shifts

The PIP2IT beam commissioning will be conducted from the PIP2IT Control Room at CMTF unless other arrangements are made. Operational shifts will be staffed as needed and in compliance with laboratory requirements. There will be at least one qualified operator on shift.

The interface between the PIP2IT control room(s) is defined in the document “Interface between PIP2IT Control Room and the Main Control Room” [5]. The protocol of communication between the PIP2IT Control Room and MCR is described in [6].

9.3. Work Planning

Commissioning activities will be planned at the weekly PIP2IT Commissioning Planning Meeting led by the L3 Commissioning Manager. The weekly plan will be based on this commissioning plan, current commissioning goals, maintenance requirements, and installation plans. The Commissioning Lead will develop daily commissioning plans based on the weekly plan and ensure their availability to commissioning operators in advance.

It expected that morning commissioning meetings will be held daily or as frequently as deemed necessary throughout the period of active commissioning to notify operating and maintenance staff of daily activities, progress, and changes.

All pertinent daily activities during the beam commissioning period will be recorded in the PIP2IT electronic logbook.

10. Beam Modes and Machine Configuration

To provide required flexibility and ensure safe operation of the machine with beam, the machine protection systems implements “machine configurations” and “beam modes”.

A “Machine Configuration” defines the portion of the beam line where the beam can go. A machine configuration also defines which channels in the MPS are active. There are 4 “machine configurations”: Ion Source, LEBT, MEBT, Full Line.

There are four “beam modes”: “Machine off”, “No Beam”, “Diagnostics”, and “Operational”. Beam modes characterize the machine’s state and control program’s readiness to start the beam. They also ensure that no insertable device can be exposed to a high-power beam.

Technical description of “machine configurations” and “beam modes” is provided in the MPS TRS document [7].

11. Software Commissioning Tools

The main control system for PIP2IT commissioning is ACNET, including its tools for:

- Turning the machine and complex devices on/off (Sequencer, ACL scripts)
- Parameter adjustments and readings (Parameter pages)
- Data visualization (Plotting tools e.g. Fast Time Plots (FTP))
- Data logging (e.g. Lumberjack datalogger)
- Save/restore/compare machine settings
- Alarms
- Restrictions for parameters ranges

Firmware/hardware/software are integrated into ACNET and configured by system experts in consultation with controls experts during installation and/or technical checkout.

In addition, some specific and specialized sub-systems (e.g. LLRF, cryo, diagnostics…) provide graphical interfaces for monitoring and basic controls.

For beam–related commissioning activities, programs developed during PIP2IT Phase-I commissioning will be used. In part, they can assist in working with diagnostics (emittance scanners, scrapers, etc.); visualize timing settings; record and plot dependencies between parameters; phase cavities one at a time in the MEBT; and measure differential trajectories. Other programs in use at Fermilab are expected to be employed as well, e.g. for tuning the beam trajectory through the centers of magnets, for stabilizing the trajectory in BPMs, and for displaying live beam parameters along the beam line. A recently commissioned program that allows changing multiple parameters according to a pre-selected schedule while recording multiple readings will be used for various purposes (e.g. de-magnetization or finding aperture limitations).

Several other programs are expected to be written or, for some of those already existing, significantly modified before the commissioning Phase-II starts, including

- MPS GUI
- Beam mode controller
- Program to control the HEBT Emittance Slit-Slit Scanner.

12. Beam Commissioning Plan

12.1. Technical prerequisites to start beam commissioning

Before starting PIP2IT Phase-II commissioning, the WFE needs be re-commissioned up to the MEBT absorber (MEBT configuration) and RF conditioning of the SRF cryomodules needs to be completed. Beam commissioning of the full line can start only if the proper conditions for passing a low-intensity beam through cryomodules to the beam dump are fulfilled. This scenario assumes that some elements of the final configuration (e.g. RF amplifiers, solenoid power supplies, or diagnostics components) can be installed later in parallel with commissioning.

The minimum set of technical prerequisites for starting the full–line beam commissioning is:

1. The entire PIP2IT beam line is assembled, and the required vacuum levels are demonstrated throughout.
2. All vacuum sensors and corresponding slow and fast valves are in place and tested.
3. Safety interlock systems are properly configured and tested.
4. The Warm Front End (WFE) is re-commissioned in all "machine configurations" up to the MEBT configuration to, at least, the "PIP-II beam parameters" excluding the bunch structure. It includes commissioning of the upgraded BPM system.
5. Both cryomodules are cold. RF cavities are conditioned. Fields in SC solenoids required to transport beam have been achieved.
6. Magnets in the MEBT downstream of the beam absorber and in the HEBT are connected to their power supplies, and their currents are calibrated.
7. A minimum set of solenoids in the cryomodules, required for passing through a pencil, low-current beam, is connected to their power supplies. The solenoids are tested to at least 50% of maximum current.
8. All available power amplifiers are connected to the SRF cavities and tested.
9. LLRF and RF PI are commissioned with no beam.
10. All diagnostics vacuum components are installed in the beam line. A minimum subset of diagnostics, additional to those from PIP2IT Phase-I commissioning, is installed and tested without beam:
    a. BPMs in the cryomodules and HEBT
    b. ACCTs on both sides of the cryomodules
    c. Reading from the beam dump
    d. DCCT
11. Radiation monitors (BLMs) are installed and connected to ACNET and the MPS.
12. The MPS is upgraded, tested in the WFE, and includes all the new channels that are required.

12.2. Instrumentation and MPS validation plan

Instrumentation and MPS are commissioned in several stages.

1. During re-commissioning of the WFE, the diagnostics and MPS components existed at PIP2IT Phase-I are tested and re-commissioned in all WFE Machine Configurations. In part, the following is demonstrated:
    a. Capability of MPS to interrupt the beam in ≤0.25 ms after the interruption detection.
    b. Low rate of false MPS interruptions with 0.55 ms beam (≤ 1/hour).
    c. Interruptions by RPU reading comparison; large beam loss to kicker protection electrodes and DPI; RF channels; and by vacuum and water.

   d. Functional MPS GUI.
   e. Established Beam modes.
   f. Established Machine configurations
   g. Tools for administrative control of the pulse length and average current.
   h. Commissioned BPMs, Allison scanners, scrapers, WFE current diagnostics.
2. Commissioning of Instrumentation and MPS continues in parallel with beam commissioning of the full line. Some of its elements:
   a. Performance of remaining BPMs (upstream portion of MEBT, cryomodules, HEBT).
   b. Current comparison by RPUs in the mode with complicated bunch patterns, if the MEBT chopping system is operational
   c. Beam interruptions by RF trips in cryomodules
   d. Current comparison between ACCTs on both sides of the cryomodules
   e. DCCT for administrative control of the average current
   f. HEBT slit-slit emittance scanner
   g. Wire scanners, RWCM, FFC in HEBT.
   h. Laser wire in MEBT if ready.

12.3. Beam commissioning sequence

The commissioning plan assumes as a pre-requisite that the WFE is re-commissioned as discussed in Section 13. Depending on readiness of components, that stage may also include commissioning of the MEBT chopper (both the kickers and absorber).

PIP2IT Phase-II commissioning consists of 3 stages:

1. Phase 1: Send beam without acceleration through both cryomodules; demonstrate operation of diagnostics and MPS. Roughly phase cavities.
   a. All SRF cavity fields are set to zero
   b. The pulse length is limited to 5 μs (Diagnostic mode)
   c. In the MEBT configuration, prepare a pencil beam in MEBT configuration by accelerating 5 mA beam in the RFQ and scraping it with M0 and M1 scrapers to 2 mA. Adjust the MEBT bunching cavities for optimum transport through cryomodules without acceleration.
   d. Set the solenoids in cryomodules to values for optimal transport of 2.1 MeV beam.
   e. Switch to Full-line configuration.
   f. Pass the pencil beam through the downstream portion of MEBT, cryomodules, and HEBT to the beam dump, increasing the pulse rate from single pulses to 20 Hz.
   g. Test BPMs as possible, ACCTs, DPI loss reading, DCCT reading
   h. Perform a rough beam alignment.
   i. Prepare 2 mA beam from 5 mA RFQ beam by removing 60% of bunches with the MEBT chopper. Set all MEBT scrapers to positions of halo-only removal. It is the main mode for further commissioning.
   j. Repeat steps 1d, 1f.

k. Turn on, one by one, SRF cavities. For each:
i. Set to 50 keV; phase using downstream BPMs; check voltage calibration using ToF between BPMs; set the cavity to -90° and the voltage optimal for downstream phasing.
l. With all cavities on, verify performance of all BPMs
m. Measure the energy with ToF movable pickup in the HEBT
n. Verify performance of slits, RWCM, HESSS FC, and FFC in HEBT
o. Verify new interruption channels in MPS (RF, vacuum, downstream RPU comparison, comparison of ACCT around cryomodules, losses to downstream MEBT scrapers and DPI, excessive DCCT current, insertion of slits or HESSS FC in Operation mode).
p. Measure the differential trajectory response to MEBT correctors. Compare with optics model.

2. Phase 2: Turn on and phase cavities. Accelerate a 5 μs, low-duty beam to 22 MeV.
    a. Diagnostic mode only. The beam pulse is prepared as in step 1i.
    b. Set cavities and solenoids to pre-calculated settings for acceleration.
    c. Pass the beam to the dump, starting from single pulses to 20 Hz. Monitor the losses with ACCT and radiation BLMs.
    d. Adjust the trajectory.
    e. Phase cavities.
    f. Measure the beam energy with ToF movable pickup.
3. Phase 3: Beam optics measurements and beam characterization.
    a. Measure the differential trajectory response to all correctors. Fit the optics model to measurements.
    b. Measure with beam size with Wire scanners in HEBT. Compare with the optics model.
    c. Record radiation from slits and determined the duty factor for slit scans.
    d. Measure the 2D phase portraits with HESSS.
    e. Measure 2D special intensity distribution with HESSS slits.
    f. Record RWCM profiles.
    g. Measure the bunch length with FFC as a function of the last SSR1 cavity's phase and amplitude. Calculate the longitudinal emittance.

13. Additional, post-commissioning beam tests

Once the commissioning goals are achieved (Section 5), and time and installed hardware capabilities permit, proceed with the following beam tests:

- Demonstrate acceleration of 2mA (average current) 550 μs long pulses to 22 MeV
- Improve performance of SRF cavities and the LLRF system with beam. These measurements are in addition to the RF tests conducted without beam and with short pulsed. The goal of these tests is to improve LLRF performance under beam loading. The required beam parameters will be specified by the LLRF group up to 2mA (average current) 550 μs long pulses to 22 MeV.
- Test of Partner's LLRF system in SSR1 cavity

- Commission the MEBT kickers. It is expected that the PIP2IT Phase-II commissioning will start without fast chopping because of unavailability of the second 200 Ohm kicker. We plan to recommission the WFE with the fast chopper after the second kicker is installed.
- Demonstrate ability to generate required bunch patterns
- RWCM measurements of cleaned bunches in HEBT
- Measure 4D distribution in HEBT
- Measure correlations between transverse-longitudinal planes in HEBT
- Emittance dilution due to chopping measured in HEBT by the slits-slit emittance scanner
- Beam orbit transverse jitter. The transverse orbit jitter was observed during the Phase I commissioning. It is important to understand the source of the jitter to be able to deliver stable beam to the Booster. Although this work can be conducted at PIP-II as well, the obtained results can affect design of AS systems causing the jitter. These studies will be conducted in along the fully length of the accelerator.
- Laser wire test. The test takes priority if the setup is ready for testing. The results of the test are needed to finalize the design of the laser wire system. The test will be conducted in MEBT.
- Reliability run with pulsed beam – demonstrate 24h beam operations with LBNF parameters.
- High power test of the MEBT absorber (beam energy of 2.1 MeV). This effort is focused on the test of the absorber performance under a high beam load (~10kW), simulating the CW operational regime.
- Acceleration of bunches with intensity twice larger than nominal.

14. Appendix A: Summary of Phase I Commissioning

The WFE has been successfully commissioned and all specification requirements have been met although not concurrently because of hardware availability limitations. The ion source provided up to ~15 mA at 30 keV in either DC or long beam pulse mode (20 Hz). The beam was scraped down (by up to ~20%) in the upstream part of the LEBT to realize a beam with nearly uniform current density distribution, which is the basis of the chosen atypical transport scheme with a relatively long section of the LEBT where the beam is fully un-neutralized. This solution does not increase the beam emittance and results in beam parameters that are nearly independent of the time structure (i.e. pulse length). The LEBT chopper, first component that inhibits the beam in the multi-tier MPS, created a macro-pulse as short as 5 □s at 20 Hz, with <100 ns fall and rise times (10-90%).

The RFQ bunched and accelerated the beam to 2.1 MeV ±1%, with 98% ±2% transmission efficiency at 5 mA, which is the nominal operational beam current for PIP-II. Proper resonance frequency control has been demonstrated with the full RF power (100 kW peak) in two regimes: pulsing at 20 Hz and CW.

The MEBT chopper created a preprogrammed bunch structure for bucket-to-bucket injection into the Booster. The beam was transported through MEBT to the end of the beam line with all the nominal aperture restrictions (kickers, DPI) without losses other than those purposely generated at the scrapers (halo removal). Bunch extinction measurements were consistent with having less than 1% of the bunch intensity left over in the unpopulated RF cycles.

The transverse emittance growth through the MEBT was within specifications (<5%), and the optics was in agreement with simulations at the 10% level. Measurements of the bunch length were consistent with expectations within the uncertainties of the measuring device (Fast Faraday Cup). Basic functionality of the Machine Protection System (MPS) was demonstrated although with significant limitations and opportunities for improvement.

15. References

#	Reference	PIP-II DocDB Document #
1	PIP2IT Shielding Assessment	
2	PIP2IT Roles and Responsibilities	4954
3	PIP2IT Hazard Analysis Document	2842
4	PIP2IT Qualified Operator	4954
5	Interface between PIP2IT CR and MCR	TBD
6	PIP2IT Control Room Communication with MCR	4937
7	PIP2IT MPS TRS	4950